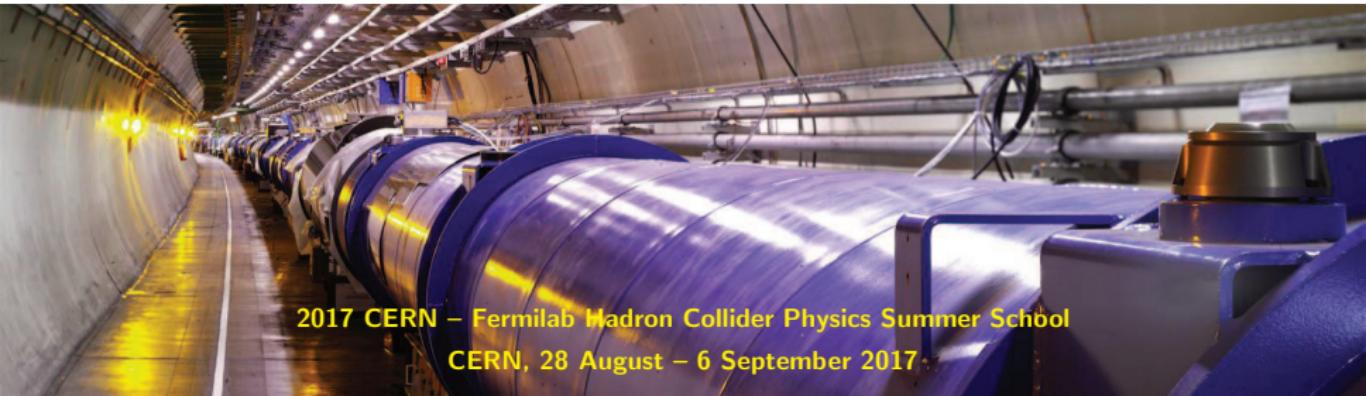


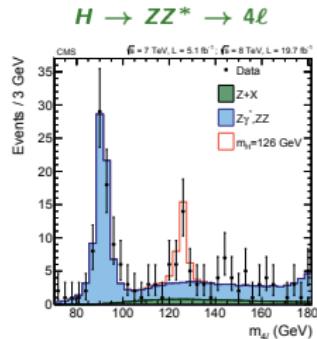
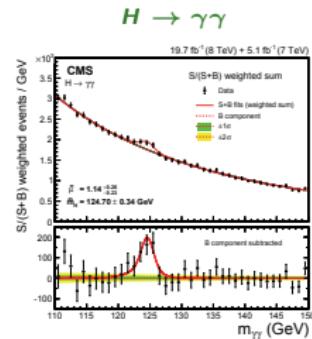
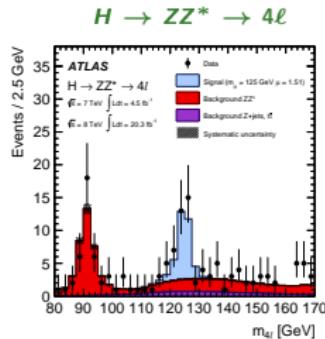
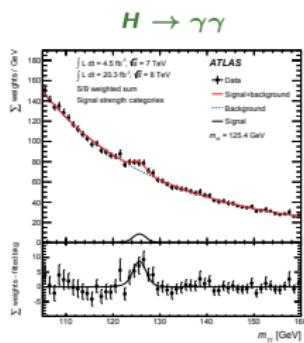
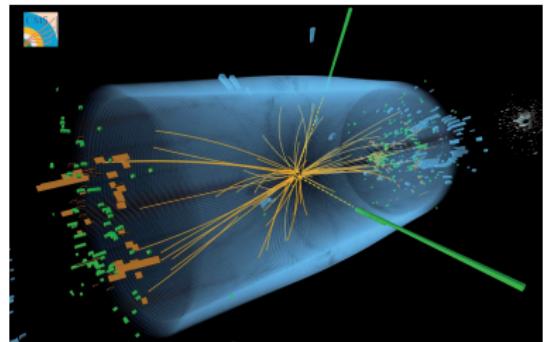
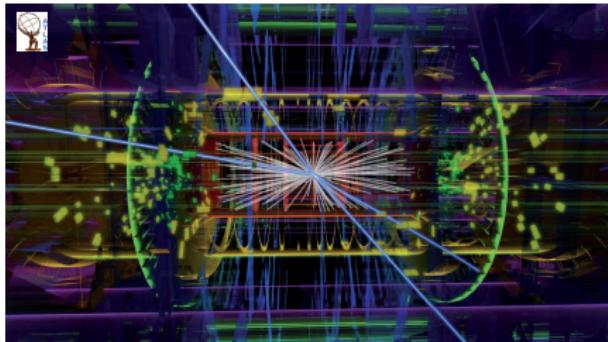
# 2. The Higgs Boson

Antonio Pich  
IFIC, Univ. Valencia - CSIC



2017 CERN – Fermilab Hadron Collider Physics Summer School  
CERN, 28 August – 6 September 2017

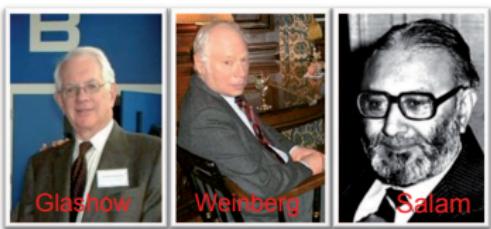
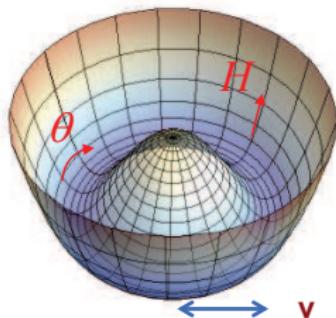
# A New Higgs-Like Boson



$$M_H = (125.09 \pm 0.21 \pm 0.11) \text{ GeV}$$

# Great success of the Standard Model

## BEGHHK ( $\equiv$ Higgs) Mechanism



$$SU(2)_L \otimes U(1)_Y \quad v = 246 \text{ GeV}$$

$$M_Z \cos \theta_W = M_W = \frac{1}{2} v g$$



Fundación  
Príncipe de Asturias



# Possible Scenarios of EWSB

① **SM Higgs:** Favoured by EW precision tests

② **Alternative perturbative EWSB:**

Scalar Doublets and singlets

$$\rho_{\text{tree}} = \frac{M_W^2}{M_Z^2 c_W^2} = \frac{\sum_i v_i^2 [T_i(T_i + 1) - Y_i^2]}{2 \sum_i v_i^2 Y_i^2}$$

③ **Dynamical (non-perturbative) EWSB:**

Pseudo-Goldstone Higgs

Scalar Resonance



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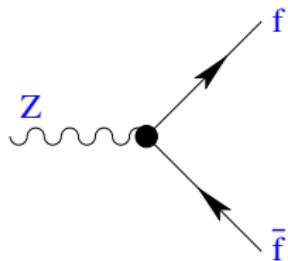
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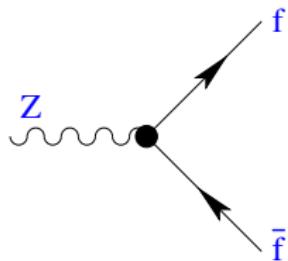




$$\Gamma(Z \rightarrow \bar{f}f) = N_f \frac{G_F M_Z^3}{6\pi\sqrt{2}} (|v_f|^2 + |a_f|^2)$$

$$N_\ell = 1 \quad , \quad N_q = N_C \left\{ 1 + \frac{\alpha_s(M_Z^2)}{\pi} + \dots \right\} \approx 3.12$$

$$\frac{\Gamma_{\text{inv}}}{\Gamma_\ell} \equiv \frac{N_\nu \Gamma(Z \rightarrow \bar{\nu} \nu)}{\Gamma_\ell} = \frac{2 N_\nu}{(1 - 4 \sin^2 \theta_W)^2 + 1} = \begin{cases} 1.955 \times N_\nu & [\alpha(m_e^2)] \\ 1.989 \times N_\nu & [\alpha(M_Z^2)] \end{cases}$$

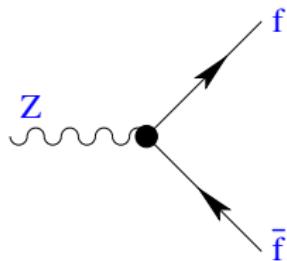


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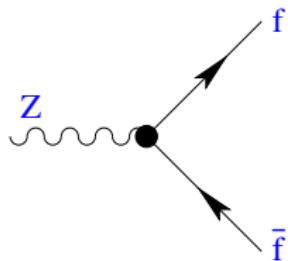
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All (NLO) EW corrections  $\rightarrow$   $N_\nu = 2.984 \pm 0.008$



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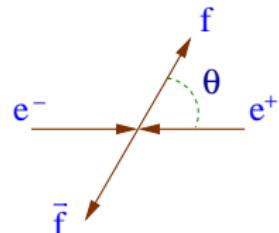
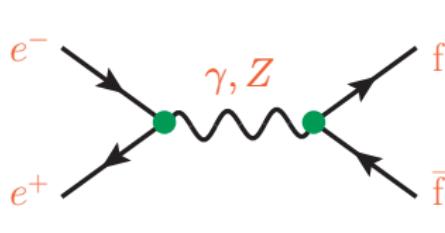
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All (NLO) EW corrections  $\rightarrow N_\nu = 2.984 \pm 0.008$

$$\frac{\Gamma(Z \rightarrow \text{had})}{\Gamma(Z \rightarrow \ell^-\ell^+)} = 20.767 \pm 0.025 \rightarrow \alpha_s(M_Z^2) = 0.1196 \pm 0.0030$$

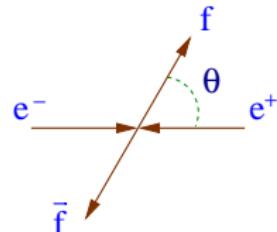
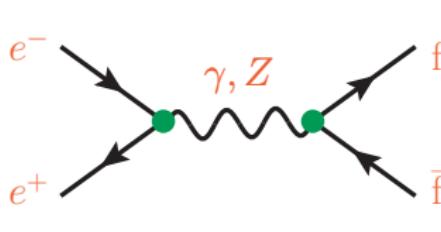
$$e^- e^+ \rightarrow f \bar{f}$$



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s} N_f \left\{ A (1 + \cos^2 \theta) + B \cos \theta - h_f [C (1 + \cos^2 \theta) + D \cos \theta] \right\}$$

$$h_f = \pm 1$$

$$e^- e^+ \rightarrow f \bar{f}$$



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s} N_f \left\{ A (1 + \cos^2 \theta) + B \cos \theta - h_f [C (1 + \cos^2 \theta) + D \cos \theta] \right\}$$

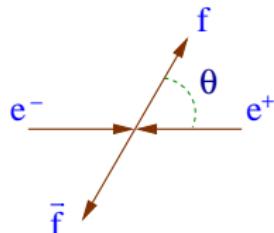
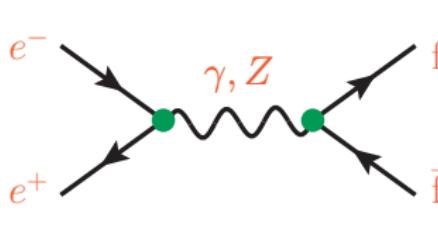
$$h_f = \pm 1$$

$$\mathcal{A}_{\text{FB}}(s) \equiv \frac{N_F - N_B}{N_F + N_B} = \frac{3}{8} \frac{B}{A},$$

$$\mathcal{A}_{\text{Pol}}(s) \equiv \frac{\sigma^{(h_f=+1)} - \sigma^{(h_f=-1)}}{\sigma^{(h_f=+1)} + \sigma^{(h_f=-1)}} = -\frac{C}{A}$$

$$\mathcal{A}_{\text{FB}}^{\text{Pol}}(s) \equiv \frac{N_F^{(h_f=+1)} - N_F^{(h_f=-1)} - N_B^{(h_f=+1)} + N_B^{(h_f=-1)}}{N_F^{(h_f=+1)} + N_F^{(h_f=-1)} + N_B^{(h_f=+1)} + N_B^{(h_f=-1)}} = -\frac{3}{8} \frac{D}{A}, \quad \sigma(s) = \frac{4\pi\alpha^2}{3s} N_f A$$

$$e^- e^+ \rightarrow f \bar{f}$$



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s} N_f \left\{ A (1 + \cos^2 \theta) + B \cos \theta - h_f [C (1 + \cos^2 \theta) + D \cos \theta] \right\}$$

$$A = 1 + 2 v_e v_f \operatorname{Re}(\chi) + (v_e^2 + a_e^2) (v_f^2 + a_f^2) |\chi|^2 \quad h_f = \pm 1$$

$$B = 4 a_e a_f \operatorname{Re}(\chi) + 8 v_e a_e v_f a_f |\chi|^2 \quad \chi = \mathcal{N} \frac{s}{s - M_Z^2 + i s \Gamma_Z / M_Z}$$

$$C = 2 v_e a_f \operatorname{Re}(\chi) + 2 (v_e^2 + a_e^2) v_f a_f |\chi|^2$$

$$D = 4 a_e v_f \operatorname{Re}(\chi) + 4 v_e a_e (v_f^2 + a_f^2) |\chi|^2 \quad \mathcal{N} = \frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}$$

$$\mathcal{A}_{\text{FB}}(s) \equiv \frac{N_F - N_B}{N_F + N_B} = \frac{3}{8} \frac{B}{A} \quad , \quad \mathcal{A}_{\text{Pol}}(s) \equiv \frac{\sigma^{(h_f=+1)} - \sigma^{(h_f=-1)}}{\sigma^{(h_f=+1)} + \sigma^{(h_f=-1)}} = - \frac{C}{A}$$

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# Z Peak ( $s = M_Z^2$ )

$$\sigma(M_Z^2) = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_f}{\Gamma_Z^2} , \quad \Gamma_f \equiv \Gamma(Z \rightarrow f \bar{f})$$

$$\mathcal{A}_{\text{FB}}(M_Z^2) = \frac{3}{4} \mathcal{P}_e \mathcal{P}_f , \quad \mathcal{A}_{\text{Pol}}(M_Z^2) = \mathcal{P}_f , \quad \mathcal{A}_{\text{FB}}^{\text{Pol}}(M_Z^2) = \frac{3}{4} \mathcal{P}_e$$

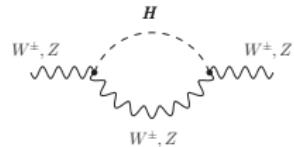
$$\mathcal{A}_{\text{LR}}(M_Z^2) \equiv \frac{\sigma_L(M_Z^2) - \sigma_R(M_Z^2)}{\sigma_L(M_Z^2) + \sigma_R(M_Z^2)} = -\mathcal{P}_e , \quad \mathcal{A}_{\text{FB}}^{\text{LR}}(M_Z^2) = -\frac{3}{4} \mathcal{P}_f$$

**Final Polarization**  $\mathcal{P}_f \equiv -\mathcal{A}_f \equiv \frac{-2 v_f a_f}{v_f^2 + a_f^2}$  **only available for**  $f = \tau$

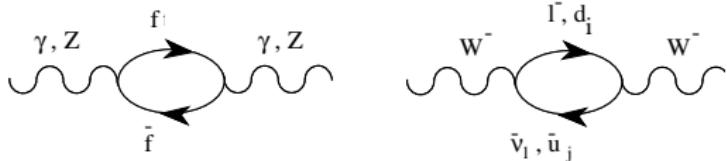
$$|v_\ell| = \frac{1}{2} |1 - 4 \sin^2 \theta_W| \ll 1$$

  $\mathcal{P}_\ell$  sensitive to higher-order corrections

# Higher-Order Corrections



$$s_W^2 \equiv \sin^2 \theta_W \quad , \quad c_W^2 \equiv \cos^2 \theta_W$$



$$\rho \equiv \frac{M_W^2}{M_Z^2 c_W^2} = \frac{1}{1 - \Delta\rho}$$

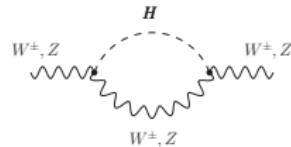
$$M_W^2 s_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F} \frac{1}{1 - \Delta\rho}$$

$$\Delta r \sim \Delta\alpha - \frac{c_W^2}{s_W^2} \Delta\rho$$

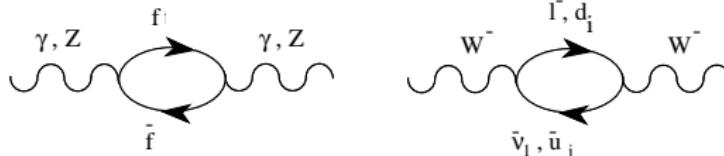
$$\Delta\rho \sim \mathcal{O}\left[\frac{\alpha}{\pi} \frac{m_t^2 - m_b^2}{M_W^2 s_W^2}, \frac{\alpha}{\pi c_W^2} \log\left(\frac{M_H^2}{M_W^2}\right)\right]$$

Veltman 1977

# Higher-Order Corrections



$$s_W^2 \equiv \sin^2 \theta_W \quad , \quad c_W^2 \equiv \cos^2 \theta_W$$



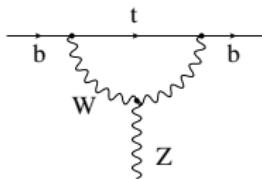
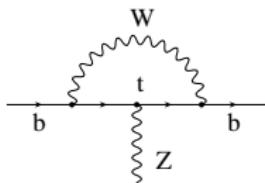
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Veltman 1977

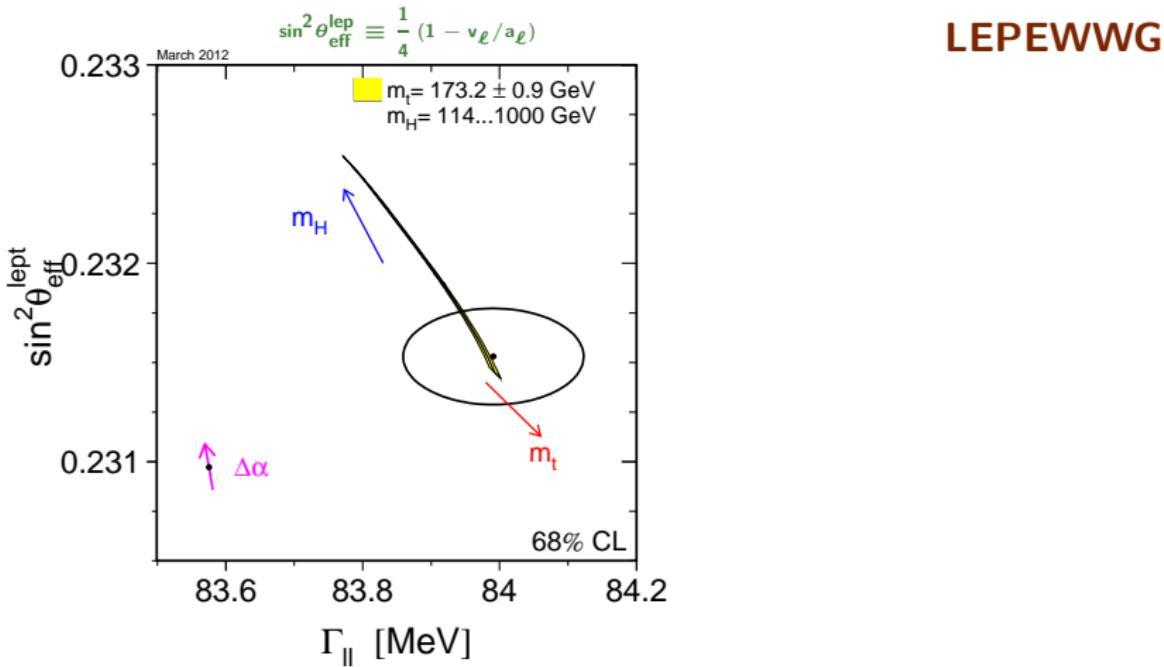


$$\Delta\Gamma(Z \rightarrow b\bar{b}) \sim \mathcal{O}\left(\frac{\alpha}{\pi} \frac{m_t^2}{M_W^2 s_W^2}\right)$$

Bernabéu–Pich–Santamaria 1988, 1991

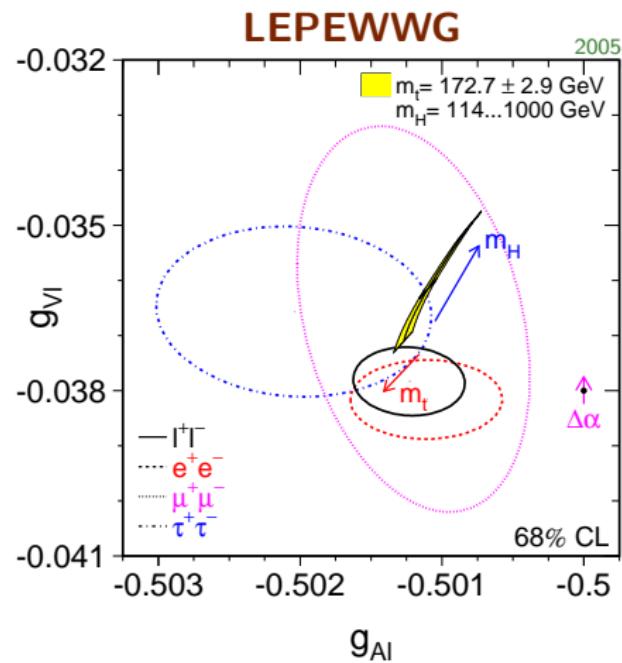
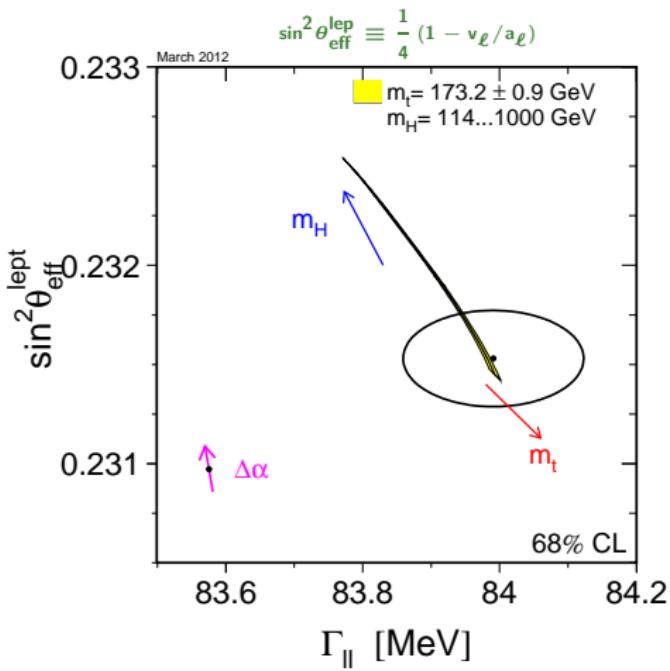
**Sensitive to Heavier Particles: Top, Higgs, New Physics**

# Evidence of Electroweak Corrections



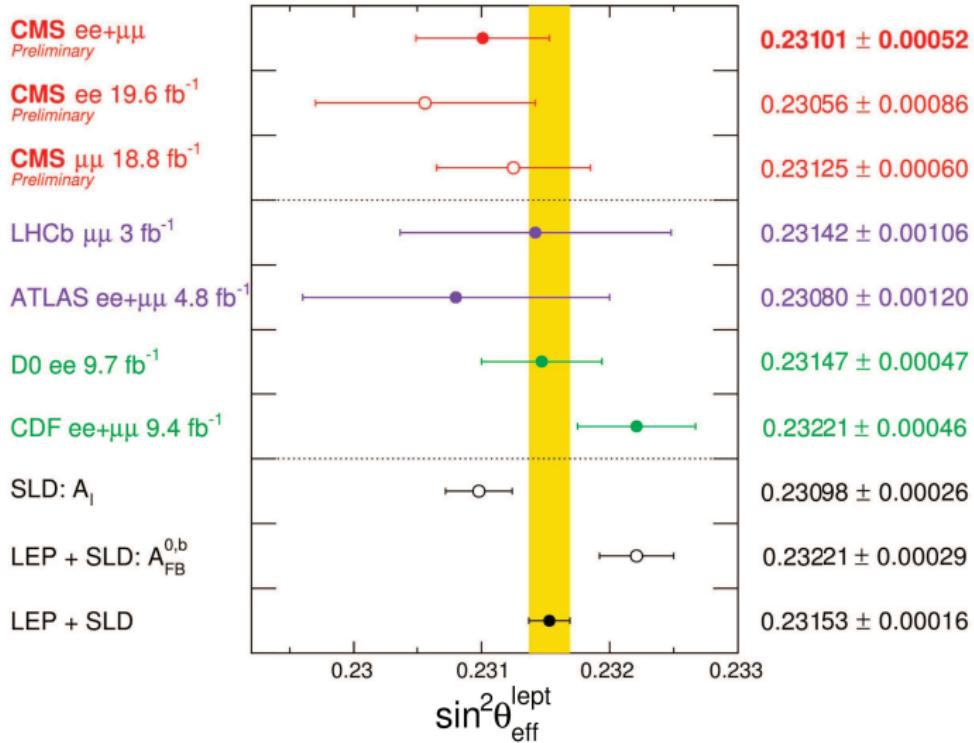
**Low values of  $M_H$  preferred**

# Evidence of Electroweak Corrections



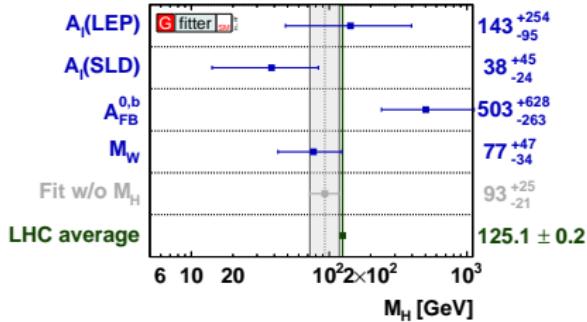
Low values of  $M_H$  preferred

$$\sin^2\theta_{\text{eff}}^{\text{lep}} \equiv \frac{1}{4} \left( 1 - \frac{\mathbf{v}_\ell}{\mathbf{a}_\ell} \right)$$

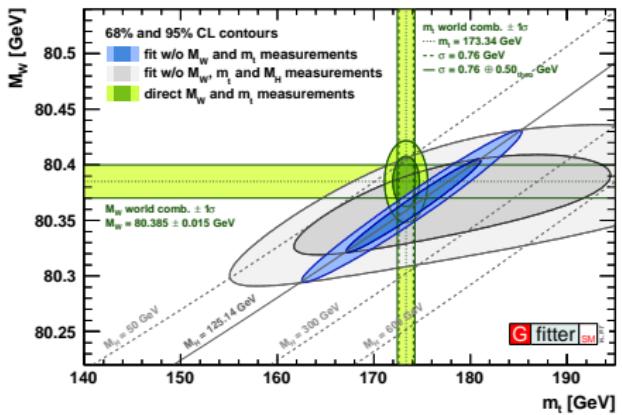
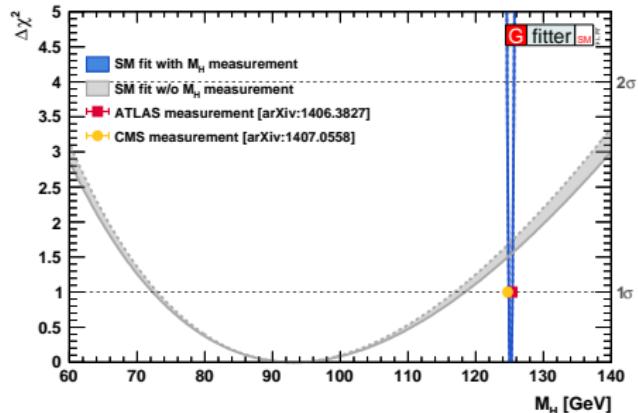


J. Alcaraz, EPS 2017

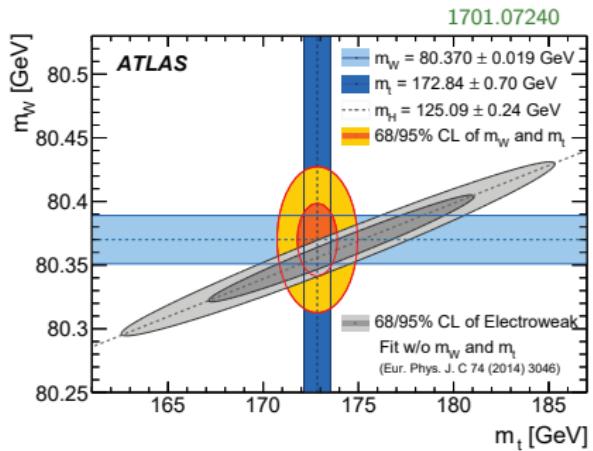
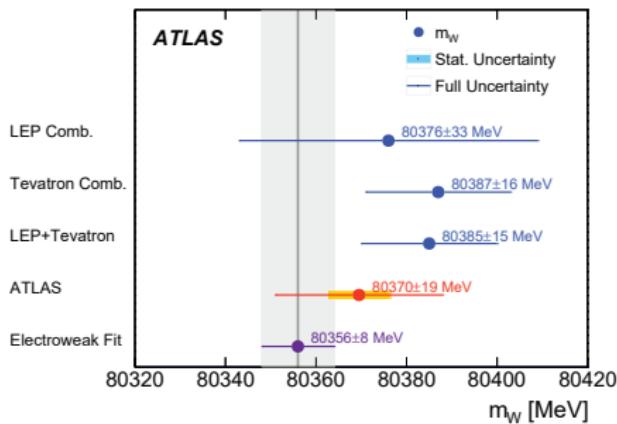
# SM Higgs



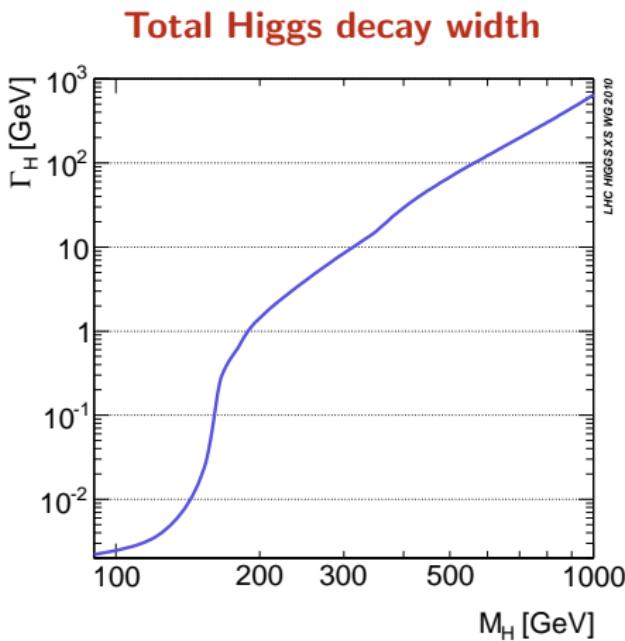
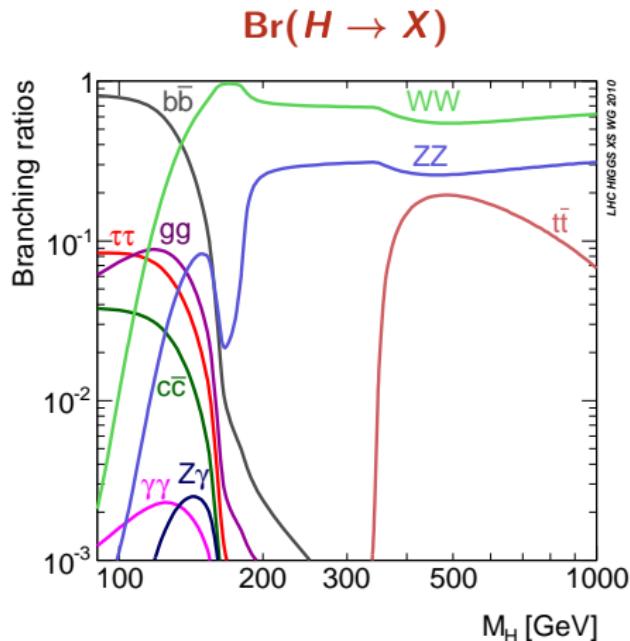
Favoured by  
EW precision tests



# First Measurement of $M_W$ at LHC



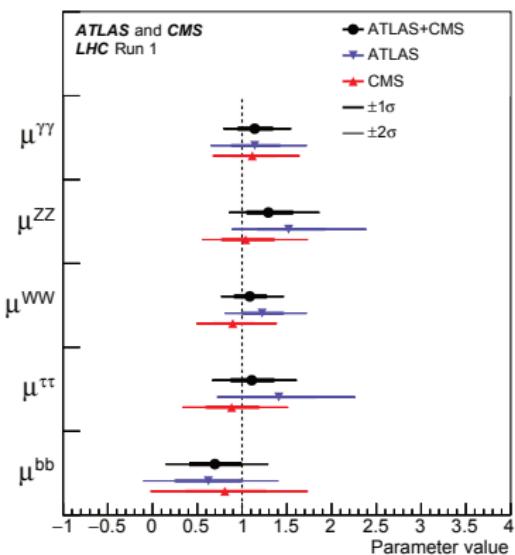
# H decays into the heaviest possible particles



Interaction proportional to mass  $(M_W^2, M_Z^2, m_f)$

# Signal Strengths

$$\mu \equiv \sigma \cdot \text{Br} / (\sigma \cdot \text{Br})_{\text{SM}}$$



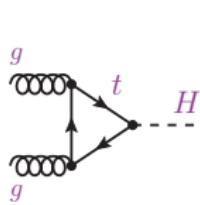
Decay Mode	ATLAS	CMS	Combined
$H \rightarrow \gamma\gamma$	$1.14^{+0.27}_{-0.25}$	$1.11^{+0.25}_{-0.23}$	$1.14^{+0.19}_{-0.18}$
$H \rightarrow ZZ^*$	$1.52^{+0.40}_{-0.34}$	$1.04^{+0.32}_{-0.26}$	$1.29^{+0.26}_{-0.23}$
$H \rightarrow WW^*$	$1.22^{+0.23}_{-0.21}$	$0.90^{+0.23}_{-0.21}$	$1.09^{+0.18}_{-0.16}$
$H \rightarrow \tau\tau$	$1.41^{+0.40}_{-0.36}$	$0.88^{+0.30}_{-0.28}$	$1.11^{+0.24}_{-0.22}$
$H \rightarrow bb$	$0.62^{+0.37}_{-0.37}$	$0.81^{+0.45}_{-0.43}$	$0.70^{+0.29}_{-0.27}$
$H \rightarrow \mu\mu$	$-0.6^{+3.6}_{-3.6}$	$0.9^{+3.6}_{-3.5}$	$0.1^{+2.5}_{-2.5}$
Combined	$1.20^{+0.15}_{-0.14}$	$0.97^{+0.14}_{-0.13}$	$1.09^{+0.11}_{-0.10}$

$$\langle \mu \rangle = 1.09^{+0.11}_{-0.10}$$

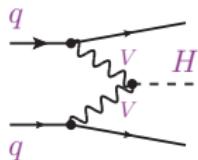
Full Run-1 Data (arXiv:1606.02266)

# Production Channels

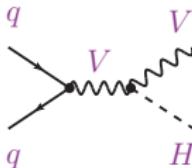
Gluon Fusion



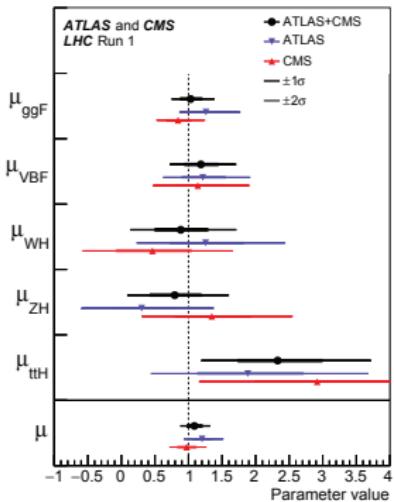
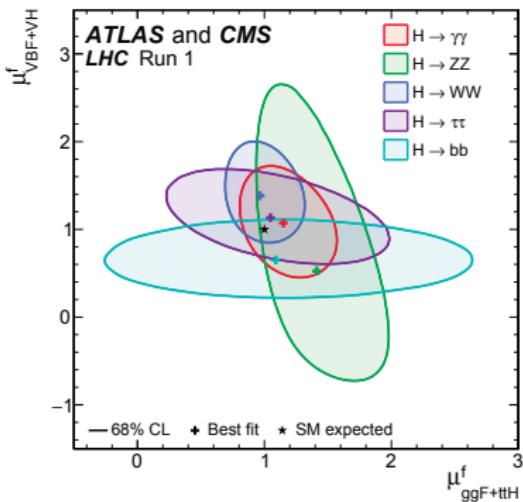
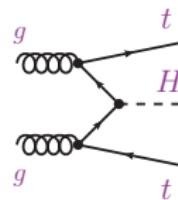
Vector Boson Fusion  
( $V = W^\pm, Z$ )



Ass.  $VH$  Production



Ass.  $t\bar{t}H$  Production



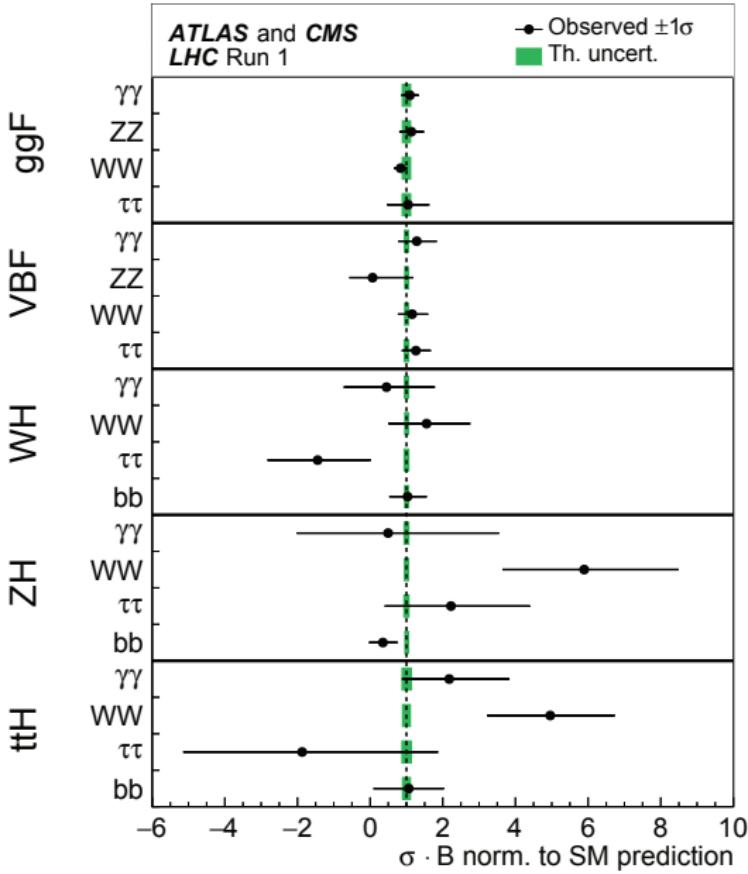
# Signal Strengths

$$\mu_i^f \equiv \frac{\sigma_i \cdot \text{Br}(H \rightarrow f)}{[\sigma_i \cdot \text{Br}(H \rightarrow f)]_{\text{SM}}} \\ \equiv \mu_i \cdot \mu^f$$

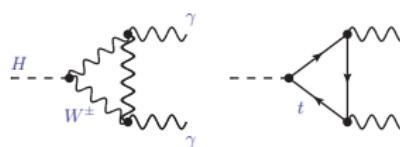
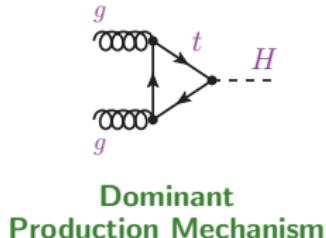
Production Channels  
&  
Decay Modes

Full Run-1 Data

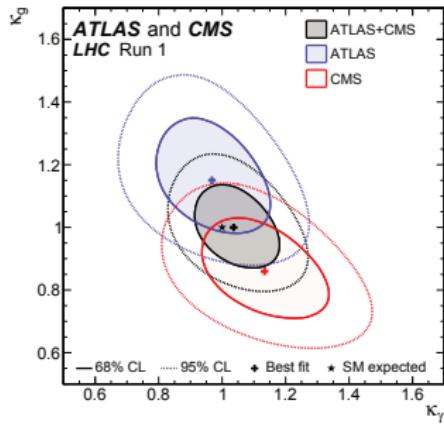
(arXiv:1606.02266)



# Strong (indirect) evidence for Higgs coupling to t



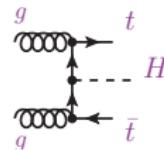
$$\Gamma \sim |\kappa_W - 0.21 \kappa_t|^2$$



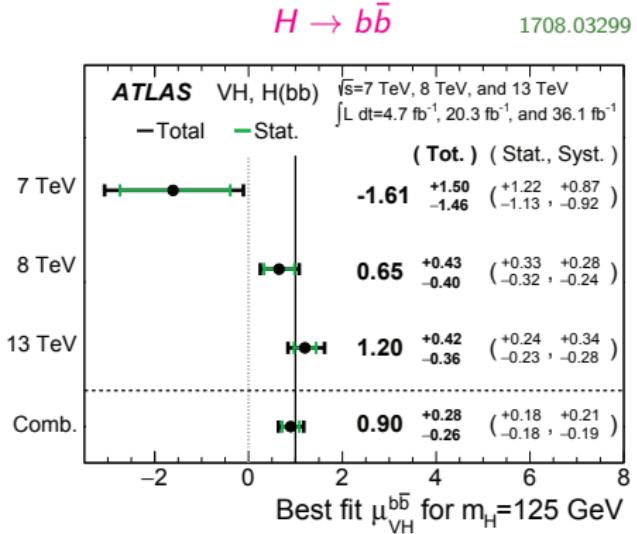
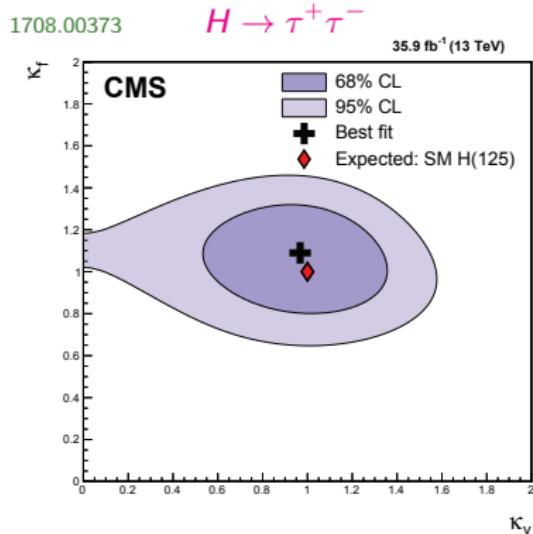
$$\kappa_i \equiv g_i/g_i^{\text{SM}}$$

$H \rightarrow \gamma\gamma$	Signal Strength
ATLAS	$1.14^{+0.27}_{-0.25}$
CMS	$1.11^{+0.25}_{-0.23}$
Combined	$1.14^{+0.19}_{-0.18}$

Direct (tree-level) sensitivity through  $t\bar{t}H$



# Strong evidence for Higgs coupling to $\tau$ and $b$

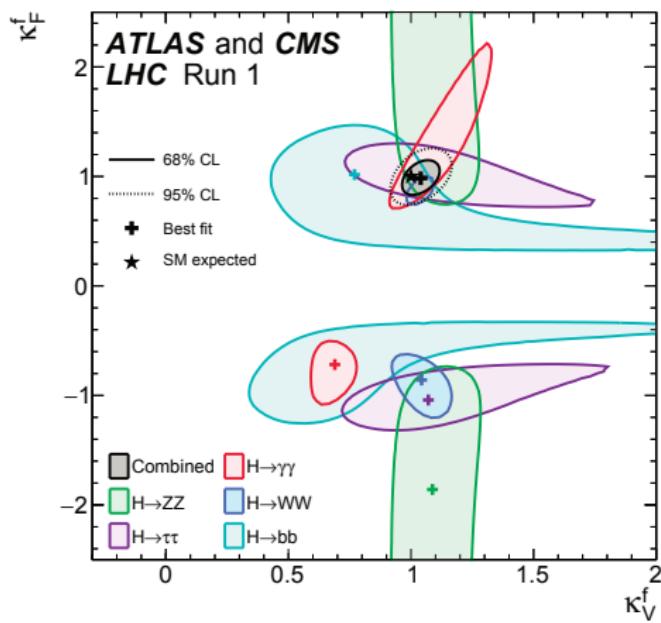


Signal Strength	ATLAS	CMS
$H \rightarrow \tau\tau$		$0.98^{+0.18}_{-0.18}$ ( $5.9\sigma$ )
$H \rightarrow b\bar{b}$	$0.90^{+0.28}_{-0.26}$ ( $3.6\sigma$ )	$1.06^{+0.31}_{-0.29}$ ( $3.8\sigma$ )

1708.00373

1708.03299 , CMS-PAS-HIG-16-044

# Effective Couplings



$$\kappa_i \equiv g_i / g_i^{\text{SM}}$$

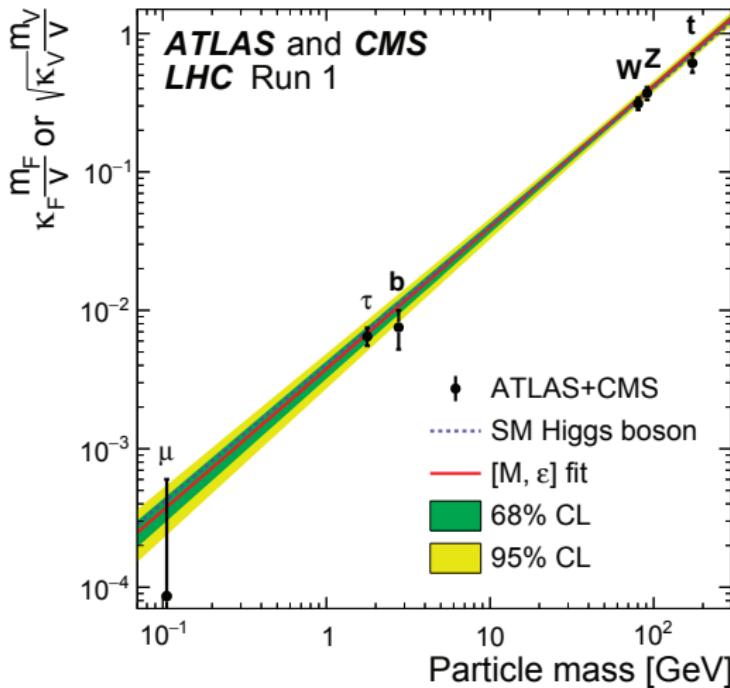
$$\begin{aligned} \sigma_{i \rightarrow H} \cdot \text{Br}_{H \rightarrow j} &= \sigma_{i \rightarrow H} \cdot \frac{\Gamma_{H \rightarrow j}}{\Gamma_H} \\ &= \left( \frac{\kappa_i \kappa_j}{\kappa_H} \right)^2 \end{aligned}$$

$$\kappa_H = \sum_j \kappa_j^2 \text{Br}_{H \rightarrow j}^{\text{SM}}$$

# It is a Higgs Boson

$$y_f = (m_f/M)^{1+\epsilon} \quad , \quad (gv/2v)^{1/2} = (M_V/M)^{1+\epsilon}$$

Ellis-You, 1303.3879



SM:  $\epsilon = 0$  ,  $M = v = 246$  GeV

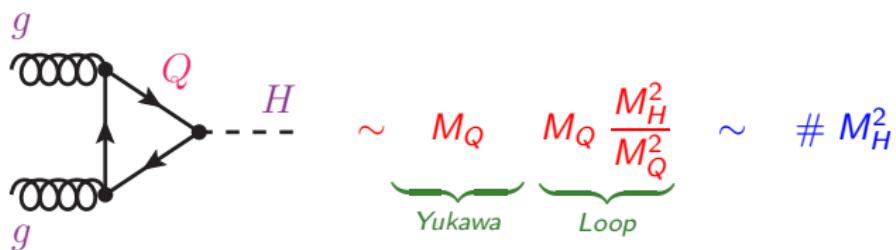
LHC-Run 1:

$$\epsilon = 0.023^{+0.029}_{-0.027}$$

$$M = (233^{+13}_{-12}) \text{ GeV}$$

# Heavier SM Generations?

$(M_Q \gg M_H)$

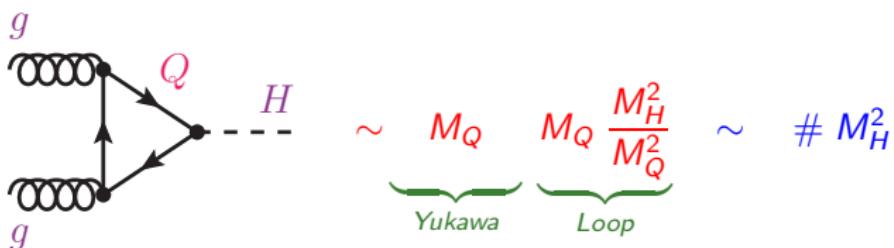


**Heavy quarks do not decouple** (result independent of  $M_Q$ )

$M_Q \rightarrow \infty$  limit already good for the top quark

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**4<sup>th</sup> Generation:**  $Q_u, Q_d$  →  $\sigma(gg \rightarrow H)_{4G} \sim 3^2 \sigma(gg \rightarrow H)_{3G}$

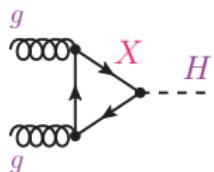
**The LHC data exclude a 4<sup>th</sup> SM Generation**

(up to fine-tuned cancellations with BSM contributions)

# QCD Exotics

V. Ilisie - AP, 1202.3430

$X \in SU(3)_C$  representation  $R$

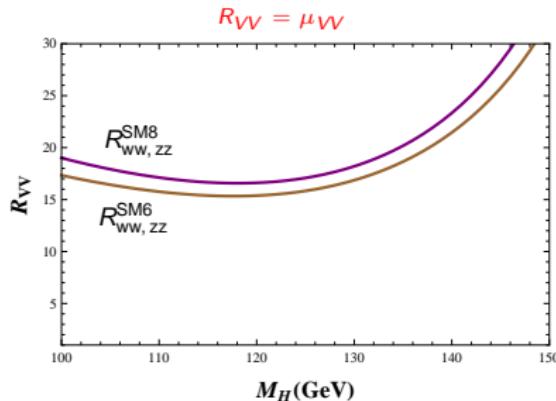
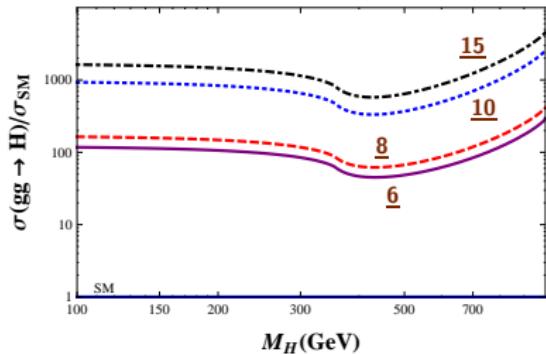


$$\sim \sum_{a=1}^{d_A} \text{Tr} [t_R^a t_R^a] = C_R d_R$$

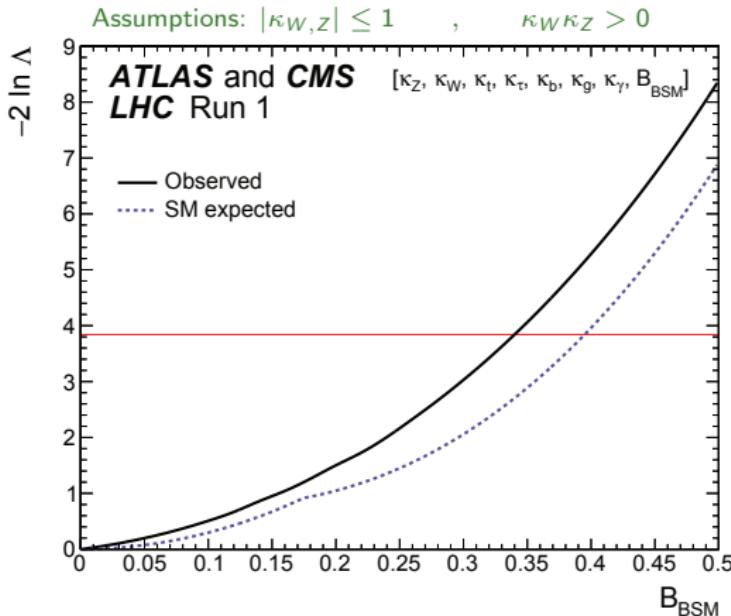
**Non decoupling:**  $\mathcal{L} = -\frac{M_X}{v} (\bar{X}X) H$

Exotic fermions in higher-colour representations could only exist provided their masses are not generated by the SM Higgs

(or fine-tuned cancelations with scalar loops)



# Invisible Higgs Width

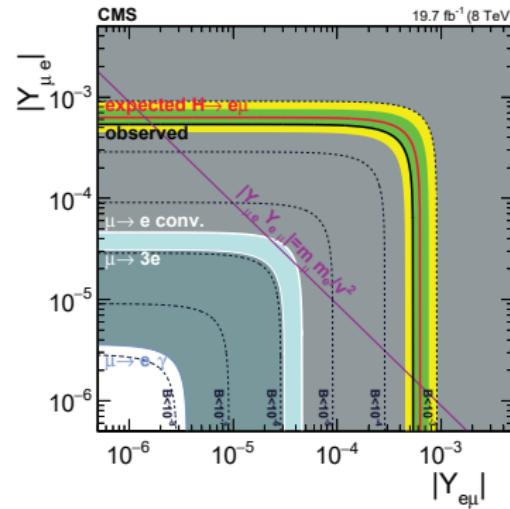
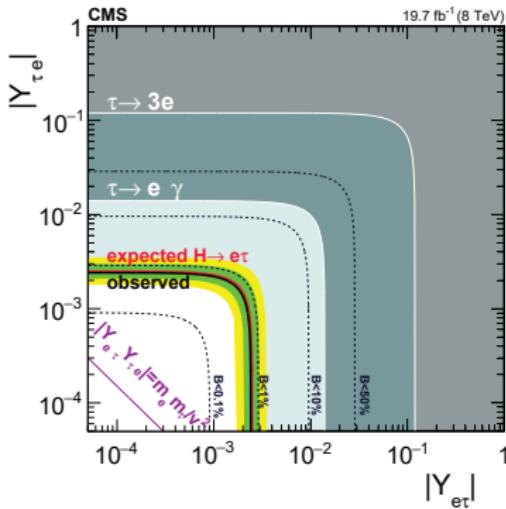


$$\text{Br}_{BSM} < 0.34 \quad (95\% \text{ CL})$$

# Lepton-Flavour-Violating Couplings

$$\mathcal{L} = -H \{ Y_{e\mu} \bar{e}_L \mu_R + Y_{e\tau} \bar{e}_L \tau_R + Y_{\mu\tau} \bar{\mu}_L \tau_R + \dots \}$$

CMS, 1607.03561



$$\text{Br}(H \rightarrow \tau e) < 0.69\% \quad , \quad \text{Br}(H \rightarrow \mu e) < 0.035\% \quad (95\% \text{ CL})$$

# Higgs-Singlet Extension of the SM

$$V(\Phi, S) = \lambda \left( |\Phi|^2 - \frac{v^2}{2} \right)^2 + (a_\Phi S + b_\Phi S^2) \left( |\Phi|^2 - \frac{v^2}{2} \right) + \frac{1}{2} M_S^2 S^2 + a_S S^3 + \lambda_S S^4$$

- Real singlet and neutral field:  $S = S^\dagger$

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  - Minima:  $\langle S \rangle = 0$  ,  $\langle \phi^{(0)} \rangle = \frac{v}{\sqrt{2}}$   $\phi^{(0)} = \frac{1}{\sqrt{2}} (v + \varphi)$
- $$M_S^2 > a_\Phi^2 / (4\lambda) > 0$$

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- Positive growing at large field values:  $\lambda, \lambda_S, b_\Phi > 0$
- Mass eigenstates (**mixing**):  $(-\frac{\pi}{2} \leq \alpha \leq \frac{\pi}{2})$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{bmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{bmatrix} \begin{pmatrix} \varphi \\ S \end{pmatrix}, \quad \tan 2\alpha = \frac{2a_\Phi v}{2v^2\lambda - M_S^2}$$

$$M_h^2 = \frac{1}{2} (\Sigma - \Delta) \quad < \quad M_H^2 = \frac{1}{2} (\Sigma + \Delta)$$

$$\Sigma = 2v^2\lambda + M_S^2, \quad \Delta = \sqrt{(2v^2\lambda - M_S^2)^2 + 4a_\Phi^2 v^2}$$

## The singlet scalar does not couple to fermions and gauge bosons

$$\kappa_V \equiv g_{hVV}/g_{hVV}^{\text{SM}} = \cos \alpha \quad , \quad \kappa_f \equiv y_{hff}/y_{hff}^{\text{SM}} = \cos \alpha$$

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$$\mu_h = \cos^2 \alpha \quad , \quad \mu_{H \rightarrow VV, f\bar{f}} = \sin^2 \alpha [1 - \text{Br}(H \rightarrow hh)]$$

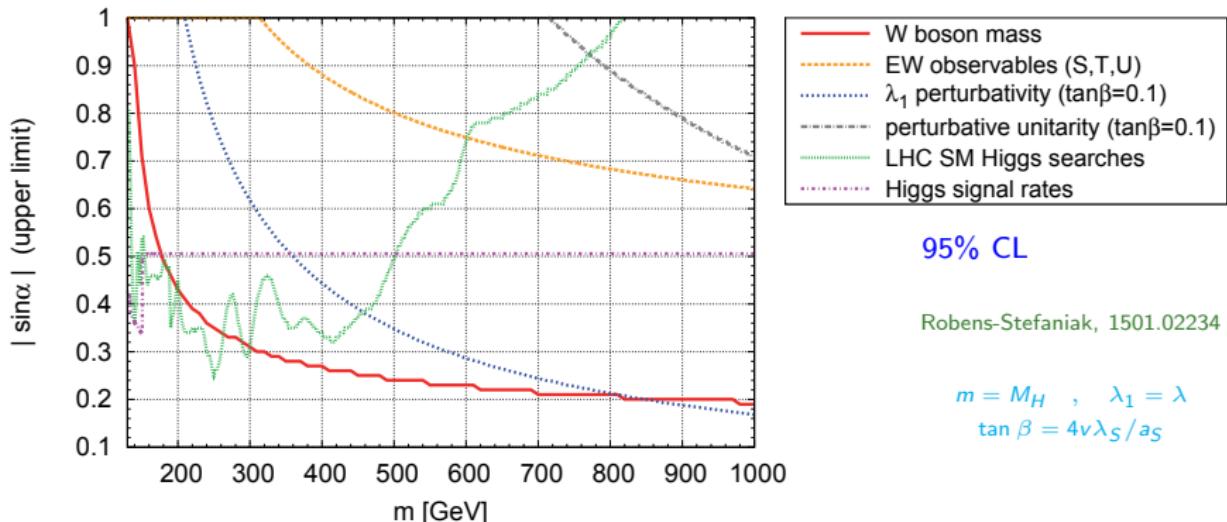
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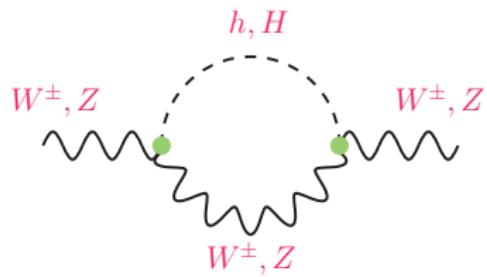
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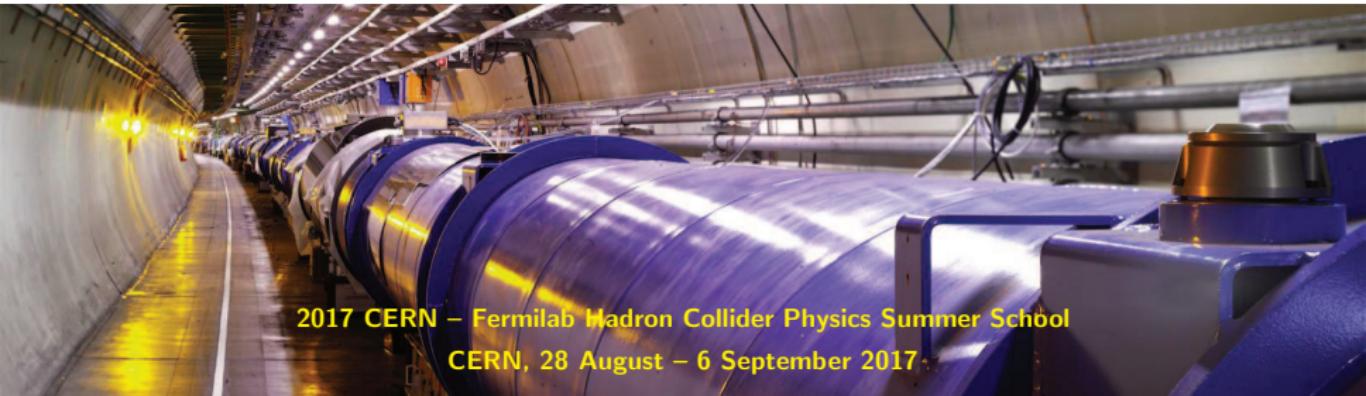


$$M_W^2 \left( 1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi\alpha}{\sqrt{2}} (1 + \Delta r)$$



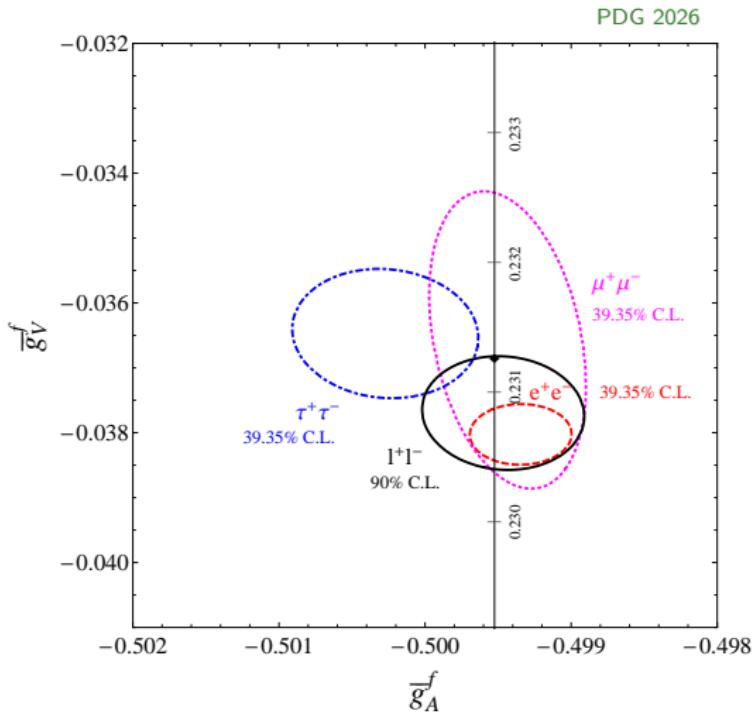
$$\delta(\Delta r) = \underbrace{\Delta r^H}_{\sin^2 \alpha} + \underbrace{\Delta r^h - \Delta r^{\text{SM}}}_{\cos^2 \alpha - 1} \propto \sin^2 \alpha$$

# Backup Slides



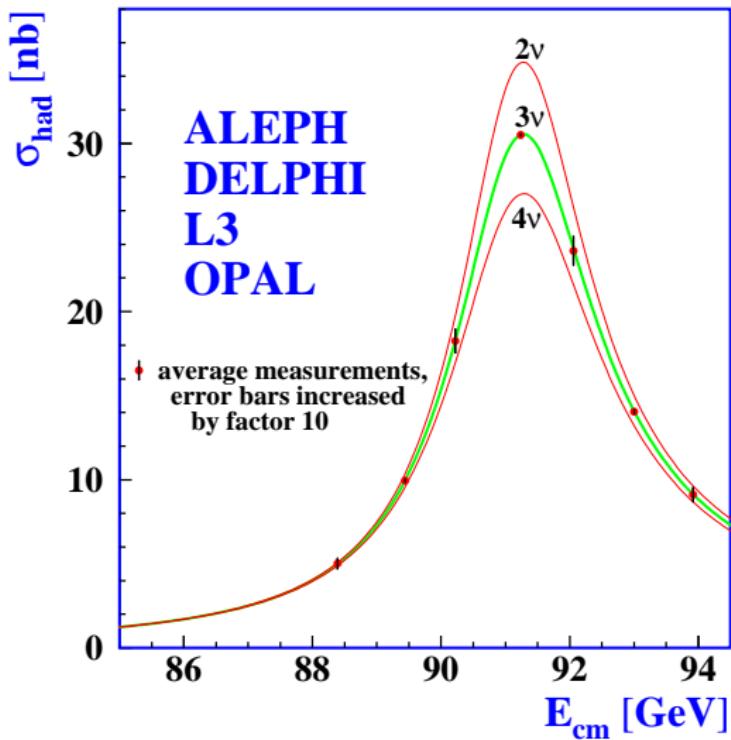
2017 CERN – Fermilab Hadron Collider Physics Summer School  
CERN, 28 August – 6 September 2017

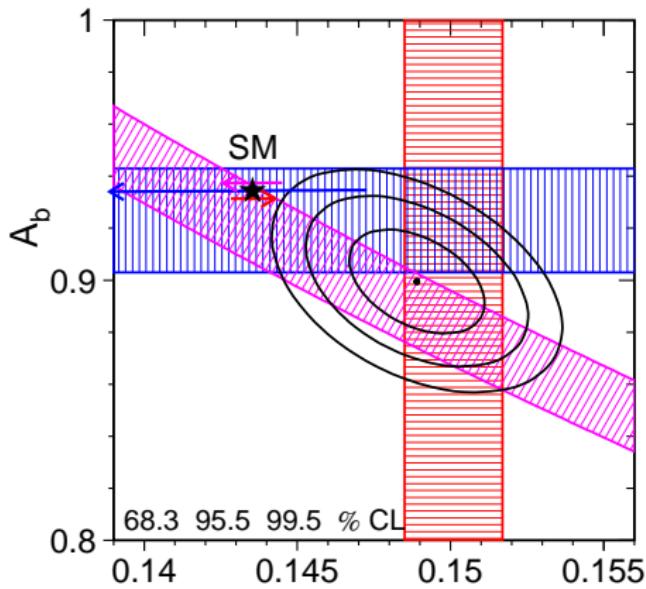
# Universality of Leptonic Z couplings



# Sensitivity to the Number of Neutrinos

hep-ex/0509008





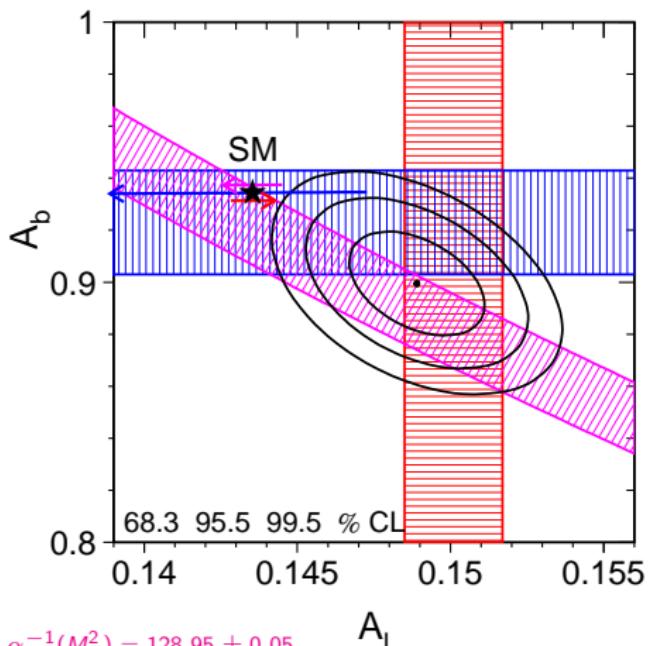
$$\alpha^{-1}(M_Z^2) = 128.95 \pm 0.05$$

$$M_H = (300^{+700}_{-186}) \text{ GeV}$$

$$m_t = (172.7 \pm 2.9) \text{ GeV}$$

 $A_l$ 

**Heavy Quarks (Leptons)**  
**Favour High (Low)  $M_H$**

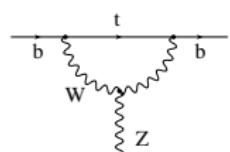
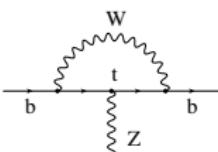
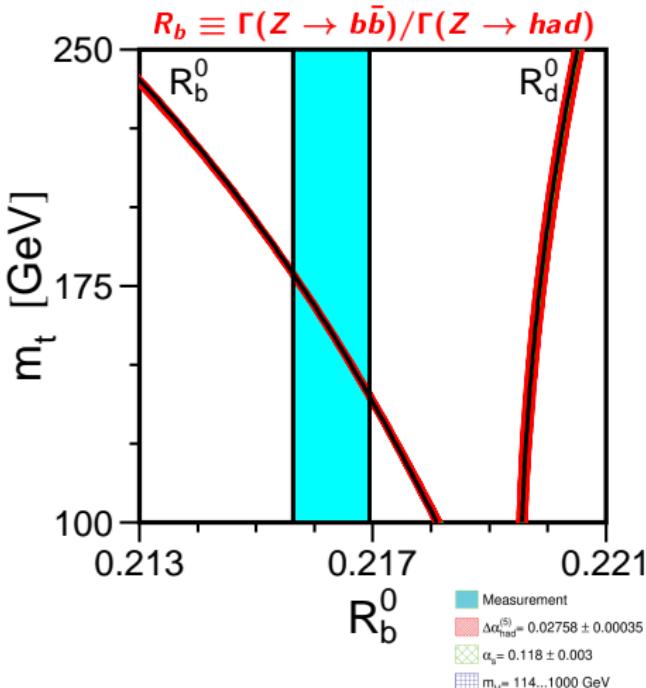


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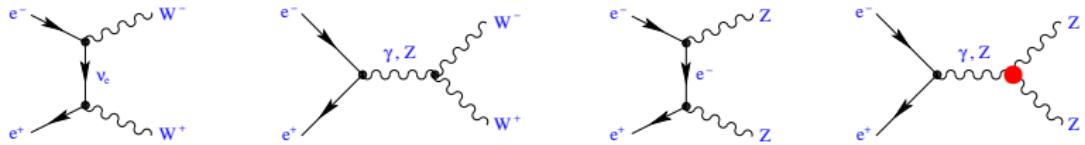
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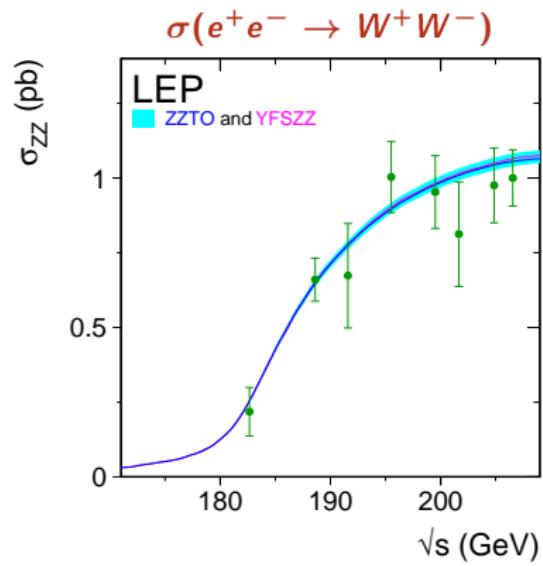
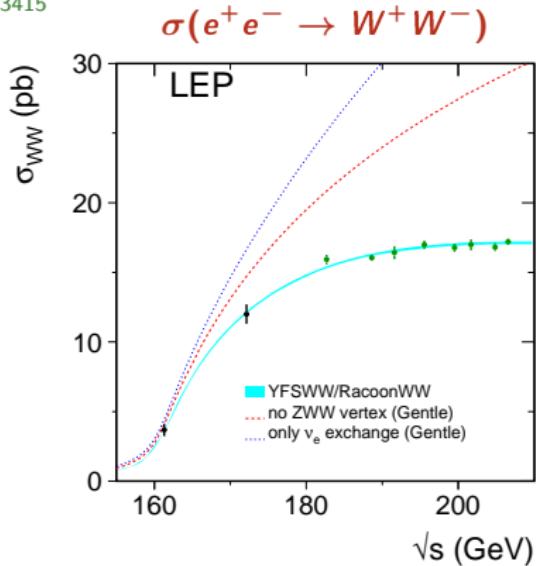
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# Evidence of Gauge Self-interactions



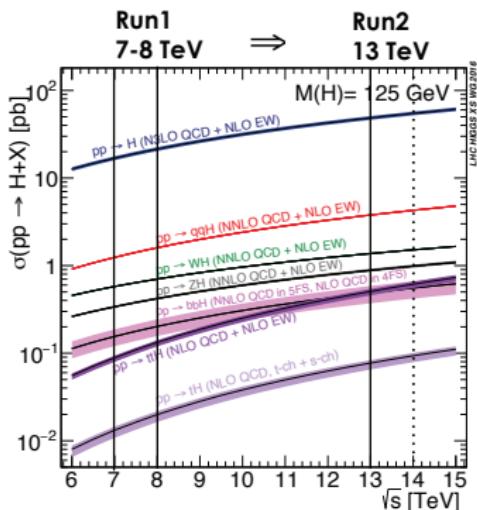
1302.3415



No evidence of  $\gamma ZZ$  or  $ZZZ$  couplings

# Higgs Production Cross Sections

Production process	Cross section [pb]		Order of calculation	
	$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 8 \text{ TeV}$		
$ggF$	$15.0 \pm 1.6$	$19.2 \pm 2.0$	NNLO(QCD) + NLO(EW)	
VBF	$1.22 \pm 0.03$	$1.58 \pm 0.04$	NLO(QCD+EW) + APPROX. NNLO(QCD)	
$WH$	$0.577 \pm 0.016$	$0.703 \pm 0.018$	NNLO(QCD) + NLO(EW)	
$ZH$	$0.334 \pm 0.013$	$0.414 \pm 0.016$	NNLO(QCD) + NLO(EW)	
$[ggZH]$	$0.023 \pm 0.007$	$0.032 \pm 0.010$	NLO(QCD)	
$ttH$	$0.086 \pm 0.009$	$0.129 \pm 0.014$	NLO(QCD)	
$tH$	$0.012 \pm 0.001$	$0.018 \pm 0.001$	NLO(QCD)	
$bbH$	$0.156 \pm 0.021$	$0.203 \pm 0.028$	5FS NNLO(QCD) + 4FS NLO(QCD)	
Total	$17.4 \pm 1.6$	$22.3 \pm 2.0$	ATLAS-CMS, 1606.02266	



## Higgs Branching Ratios

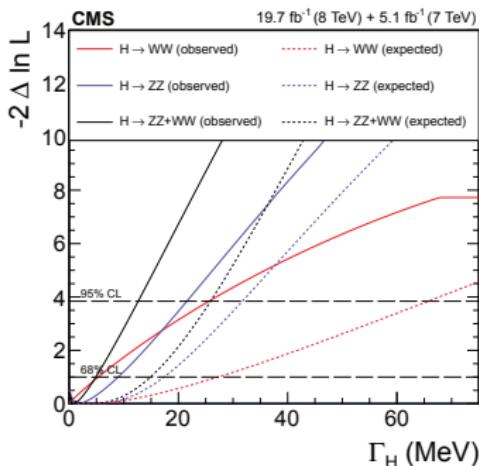
Decay mode	Branching fraction [%]
$H \rightarrow bb$	$57.5 \pm 1.9$
$H \rightarrow WW$	$21.6 \pm 0.9$
$H \rightarrow gg$	$8.56 \pm 0.86$
$H \rightarrow \tau\tau$	$6.30 \pm 0.36$
$H \rightarrow cc$	$2.90 \pm 0.35$
$H \rightarrow ZZ$	$2.67 \pm 0.11$
$H \rightarrow \gamma\gamma$	$0.228 \pm 0.011$
$H \rightarrow Z\gamma$	$0.155 \pm 0.014$
$H \rightarrow \mu\mu$	$0.022 \pm 0.001$

# Higgs Width

Sensitivity to  $\Gamma_H$  off-shell:

Caola-Melnikov, Kauer-Passarino, Campbell et al

$$\frac{d\sigma_{gg \rightarrow H \rightarrow ZZ}}{dm_{ZZ}^2} \sim \frac{g_{ggH}^2 g_{hZZ}^2}{(m_{ZZ}^2 - M_H^2)^2 + M_H^2 \Gamma_H^2}, \quad \sigma_{gg \rightarrow H \rightarrow ZZ} \sim \begin{cases} \frac{g_{ggH}^2 g_{hZZ}^2}{M_H \Gamma_H} & (\text{on-shell}) \\ \frac{g_{ggH}^2 g_{hZZ}^2}{4M_Z^2} & (m_{ZZ} > 2M_Z) \end{cases}$$



CMS, 1605.02329:

$$\Gamma_H < 3.2 \Gamma_H^{\text{SM}} = 13 \text{ MeV} \quad (95\% \text{ CL})$$

ATLAS, 1503.01060:

$$\Gamma_H < 22.7 \text{ MeV}$$

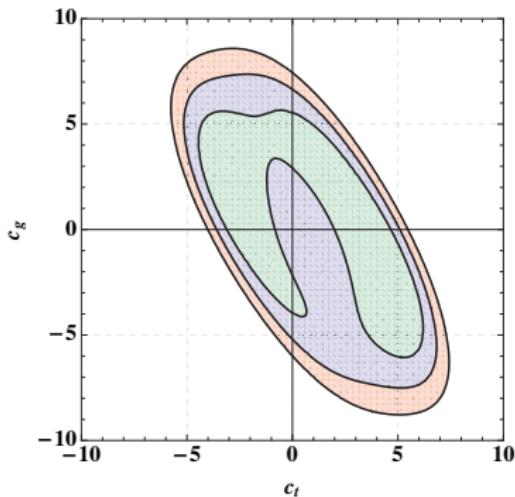
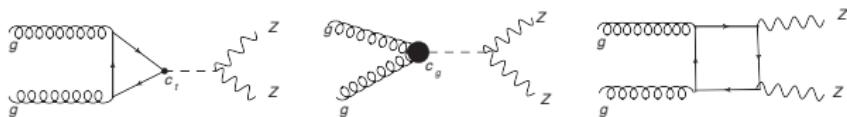
Assumes constant couplings unrelated to  $\Delta\Gamma_H$

Englert-Spannowsky, 1405.0285

# Alternative analysis:

Azatov et al, 1406.6338

$$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t} t H + \frac{g_s^2}{48\pi^2 v^2} c_g G_{\mu\nu} G^{\mu\nu} H$$



$$\sigma \sim |c_t + c_g|^2 \quad (\text{on-shell})$$

$$\mathcal{M}_{c_g} \sim c_g \hat{s} \quad (\hat{s} \gg m_t^2)$$